NUMERICAL STUDY OF CRASHWORTHINESS ON HONEYCOMB FILLER SUBJECTED TO IMPACT LOADING

TAN SZE PEI

MASTER OF SCIENCE

UNIVERSITI MALAYSIA PAHANG

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

____

(Supervisor's Signature)

Full Name : DR. SITI NADIAH BT MOHD SAFFE

Position : SENIOR LECTURER

Date :

STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

____

(Student's Signature)

Full Name : TAN SZE PEI

ID Number : MSM15002

Date :

NUMERICAL STUDY OF CRASHWORTHINESS ON HONEYCOMB FILLER SUBJECTED TO IMPACT LOADING

TAN SZE PEI

Thesis submitted in fulfillment of the requirements
for the award of the degree of
Master of Science

Faculty of Engineering Technology

UNIVERSITI MALAYSIA PAHANG

DECEMBER 2019

ACKNOWLEDGEMENTS

I would like to thank my supervisor Dr. Siti Nadiah bt Mohd Saffe of the Faculty of Technology Engineering at Univerity Malaysia Pahang. The door to Dr. Siti office is always open whenever I ran into a trouble spot or had a question about my research or writing. She consistently allowed this thesis to be my own work, but steered me in the right direction whenever she thought I needed it. I would also like to thank my co-supervisor Madam Siti Aishah bt Rusdan and Madam Nurul Nadiah for the encouragement and help whenever I needed it throughout my entire length of study.

I take this opportunity to express gratitude to all of the Department faculty members for their help and support. I also thank my friends whom I made during the years of researching and writing this thesis.

Finally, I must express my very profound gratitude to my parents and my family for continuous support and encouragement throughout the years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

ABSTRAK

Pengisi sarang lebah adalah komponen yang baik bagi peralatan penyerapan tenaga untuk struktur kereta. Banyak kajian berkenaan pengisi sarang lebah di bawah impak hadapan beban paksi telah dijalankan dan dicadangkan di dalam kajian literatur. Namun, apabila kemalangan sebenar terjadi, perlanggaran bukan sahaja datang daripada impak hadapan (beban paksi), malah dari pelbagai sudut (beban serong). Oleh itu, ketahanan perlanggaran daripada pelbagai sudut yang paling penting di dalam rekaan keselamatan kenderaan. Kriteria ketahanan perlanggaran yang dikenali sebagai penyerapan tenaga (EA) dan penyerapan tenaga khusus (SEA) adalah berkait dengan parameter pemuatan. Keselamatan merupakan satu ciri keutamaan di dalam reka bentuk sesebuah penyerap tenaga. Walau bagaimanapun, tidak mengenakan berat berlebihan ke atas penyerap tenaga juga menjadi perhatian pengeluar. Hal ini adalah kerana semakin ringan sesebuah kenderaan, semakin sedikit bahan bakar yang digunakan untuk lebih mesra alam . Objektif utama kajian ini adalah untuk mengkaji prestasi pengisi sarang lebah dengan rekabentuk keratan rentas yang berbeza dengan ketebalan yang dikenakan pada sudut impak pemuatan yang berbeza. Penyiasatan ini dijalankan secara Finite Element (FE) menggunakan perisian ABAQUS. Penyiasatan dilaksanakan dengan mengenakan impak dinamik terhadap semua model FE pengisi sarang lebah. Penyiasatan numerikal mengkaji tindak balas tiga reka bentuk geometri pengisi iaitu pengisi sarang lebah berbentuk bulatan, heksagon dan struktur berbilang sel. Diameter bagi setiap satu sel pengisi sarang lebah ditetapkan kepada 10.4 mm. Tiga ketebalan berbeza bagi setiap sel berukuran t = 0.06 mm, 0.12 mm dan 0.18 mm telah dikaji. Semua model dijalankan dengan menggunakan impak dinamik beban paksi dan beban serong yang bersudut θ = 0°, 10°, 20° dan 30°. Bahan logam yang digunakan terhadap setiap model adalah aloi aluminium AA6060-T4. Berdasarkan rekabentuk struktur tersebut, pengisi sarang lebah berbentuk heksagon adalah reka bentuk yang terbaik. Keputusan bagi EA, SEA dan CFE untuk pengisi sarang lebah berbentuk heksagon ialah 120% lebih tinggi berbanding pengisi sarang lebah berbentuk bulatan dan 230 % lebih tinggi daripada pengisi berbilang sel. Berdasahkan keputusan analisia ini boleh dirumuskan bahawa apabila ketebalan pengisi sarang lebah meningkat, maka prestasi kriteria crashworthiness juga meningkat. Apabila ketebalan meningkat daripada 0.06 mm ke 0.12 mm, EA dan CFE meningkat lebih kurang 290 % dan SEA meningkat lebih kurang 150 %. Apabila ketebalan bertambah daripada 0.12 mm ke 0.18mm, EA, SEA dan CFE masing-masing meningkat lebih kurang 170 %, 120 % dan 190 %. Apabila ketebalan bertambah daripada 0.06 mm ke 0.18, EA, SEA dan CFE masing-masing juga dianggarkan meningkat sebanyak 500 %, 170 % dan 550 %. Peningkatan tersebut adalah lebih tinggi daripada nisbah ketebalan iaitu sebanyak 200 % bagi peningkatan daripada 0.06 mm ke 0.12 mm, 150 % bagi peningkatan daripada 0.12 mm ke 0.18 mm dan 300 % bagi peningkatan 0.06 mm ke 0.18 mm. Akhir sekali, beban paksi dan beban sarang pengisi sarang lebah bersudut θ = 0° - 30° juga dikaji. Keputusan menunjukkan prestasi EA dan SEA menurun apabila sudut, θ meningkat. Kesimpulannya, keseluruhan keputusan menunjukkan pengisi sarang lebah berbentuk heksagon adalah model terbaik dari segi geometri, ketebalan dan sudut pemuatan.

ABSTRACT

Honeycomb filler is known as a good filler for energy absorbing devices in car. Many types of research about honeycomb filler under axial impact had been done and proposed in the literature. However, when it comes to the real situation in an accident, a collision is not only coming from a frontal impact (axial loading). A collision might also come from a different angle (oblique loading). Therefore, crashworthiness in several impact angles are important concern in designing a safe vehicle. The crashworthiness criteria, namely energy absorption (EA) and specific energy absorption (SEA) are related to loading parameters. Safety is the main concern in designing an energy absorber. However, reducing the extra weight caused by the energy absorber is also one of the concerns for manufacturers. This is because the lighter the weight the vehicle has the lesser fuel is consumed to be eco-friendly. In this study, the main objective is to study the performance of honeycomb fillers by different cross-sectional design versus thickness subjected to different angles of impact loading. The investigation is carried out by Finite Element (FE) simulation using ABAQUS software. The investigations of all FE models are carried out by the dynamic impact test. Numerical investigation studies the reaction of three types of honeycomb filler geometric designs which are circular honeycomb filler, hexagon honeycomb filler and multicell. The diameter of every single cell for honeycomb filler is fixed at 10.4 mm. Three different thicknesses of every cell are investigated which are t = 0.06 mm, 0.12 mm, and 0.18 mm. All models are carried out by dynamic impact with both axial and oblique loading which θ = 0°, 10°, 20°, and 30°. The material assigned to all models is aluminium alloy AA6060-T4. According to simulation result in this study, hexagon honeycomb filler is the best structural design. The result of EA, SEA, and CFE of hexagon honeycomb filler is 120 % higher than circular honeycomb filler and 230 % higher than multicell filler. The crashworthiness is influenced by the thickness of honeycomb filler, the thickness of honeycomb filler increased, then crashworthiness criteria performance increased. When thickness increased from 0.06 mm to 0.12 mm, the EA and CFE increased by approximately 290 % and SEA increased by approximately 150 %. When thickness increased from 0.12 mm to 0.18 mm, the EA, SEA, and CFE increased by approximately 170 %, 120 % and 190 %, respectively. When thickness increased from 0.06 mm to 0.18 mm, the EA, SEA, and CFE increased by approximately 500 %, 170 %, and 550 %, respectively. The increment is much higher than the aspect ratio of thickness of 200 %, 150 %, and 300 % respect to 0.06 mm to 0.12 mm, 0.12 mm to 0.18 mm, and 0.06 mm to 0.18 mm. Lastly, the axial loading and oblique loading of honeycomb fillers with angles, θ = 0° - 30° are studied. Results showed that the performance of EA and SEA decreased when angles, θ increased. In conclusion, the overall result showed that hexagon honeycomb filler is the best model in terms of geometry, thickness, and angle of loading.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

Fds	Area under the load-displacement
m	Mass of the component
h	Thickness of shell
C	Material-dependent constant
D	Diameter
D_{shell}	Diameter of the shell
E	Energy absorbed
M_0	Column wall flow stress
c	Width of the column
H	Half-fold length
d	Crushing distance
$\mathrm{d}_{\mathrm{max}}$	Effective crushing distance
$\sigma_{0.2}$	0.2% plastic strain
σ_{Ult}	Ultimate stress
σ_0	Flow stress
β	Hinge rotation angle
P_d	Dynamic crash force
P_s	Static crash force
V_0	Initial impact velocity
σ_0^d	Dynamic flow stress
σ_0^s	Static flow stress
P	Material constants determined from the dynamic tensile tests
^{o}	Degree of angles
θ	Angle of loading
r	Radius
t	Thickness
s	Displcement

LIST OF ABBREVIATIONS

CAE	Computer-Aided Engineering
CFE	Force Efficiency Crush
CO_2	Carbon dioxide
EA	Energy Absorption
FE	Finite Element
FEM	Finite Element Method
FGH	Functionally Graded Honeycomb
LTVs	Light trucks and vans
MCF	Mean Crush Force
PCF	Peak Crush Force
RSM	Response Surface Method
SE	Stroke Efficiency
SEA	Specific Energy Absorption
SLTV	Supervisory LTV
SUVs	Sport Utility Vehicles

REFERENCES

Aaron, V., Adibi-Sedeh, A. H., Nagarajan, H., and Bahr, B. (2003). Determination of strength characteristics of aluminum honeycomb material subjected to out-of-plane compression using finite element analysis. *Advances in Structures*, 427–432.

Abaqus Analysis User's Manual 6.10. (2010). *Dassault Systèmes*. Retrieved from *https://www.sharcnet.ca/Software/Abaqus610/Documentation/docs/v6.10/books/usb/default.htm?startat=pt06ch26s06alm16.html*

Abramowicz, W. (1981). Simplified crushing analysis of thin-walled columns and beams. *Engineering Transactions*, 29: 3–27.

Abramowicz, W. (1983). The effective crushing distance in axially compressed thin-walled metal columns. *International Journal of Impact Engineering*, 1(3): 309–317.

Abramowicz, W., and Jones, N. (1984). Dynamic axial crushing of square tubes. *International Journal of Impact Engineering*, 2(2): 179–208.

Abramowicz, W., and Jones, N. (1986). Dynamic progressive buckling of circular and square tubes. *International Journal of Impact Engineering*, 4(4): 243–270.

Abramowicz, W., and Wierzbicki, T. (1989). Axial crushing of multicorner sheet metal columns. *Journal of Applied Mechanics*, 56(1): 113–120.

Ahmad, Z., and Thambiratnam, D. P. (2009). Dynamic computer simulation and energy absorption of foam-filled conical tubes under axial impact loading. *Computers & Structures*, 87(3–4): 186–197.

Ahmad, Z., Thambiratnam, D. P., and Tan, A. C. C. (2010). Dynamic energy absorption characteristics of foam-filled conical tubes under oblique impact loading. *International Journal of Impact Engineering*, 37(5): 475–488.

Akerstrom, T., and Wierzbicki, T. (1977). Dynamic crushing of strain rate sensitive box columns. In *SAE Technical Papers* (p. SAE Paper No. 770592). Southfield, Michigan, April 18-20: In Second International Conference on Vehicle Structural Mechanics.

Aktay, L., Kröplin, B.-H., Toksoy, A. K., and Güden, M. (2008). Finite element and coupled finite element/smooth particle hydrodynamics modeling of the quasi-static crushing of empty and foam-filled single, bitubular and constraint hexagonal- and square-packed aluminum tubes. *Materials & Design*, 29(5): 952–962.

Alexander, J. M. (1960). An approximate analysis of the collapse of thin cylindrical shells under axial loading. *Quarterly Journal of Mechanics and Applied Mathematics*, 13(1): 10–15.

Alghamdi, A. A. A. (2001). Collapsible impact energy absorbers: An overview. *Thin-Walled Structures*, 39(2): 189–213.

Asanjarani, A., Dibajian, S. H., and Mahdian, A. (2017). Multi-objective crashworthiness optimization of tapered thin-walled square tubes with indentations. *Thin-Walled Structures,* 116: 26–36.

Avalle, M., Belingardi, G., and Montanini, R. (2001). Characterization of polymeric structural foams under compressive impact loading by means of energy-absorption diagram. *International Journal of Impact Engineering*, 25(5): 455–472.

Baroutaji, A., Sajjia, M., and Olabi, A.-G. (2017). On the crashworthiness performance of thin-walled energy absorbers: Recent advances and future developments. *Thin-Walled Structures*, 118: 137–163.

Bi, J., Fang, H., Wang, Q., and Ren, X. (2010). Modeling and optimization of foam-filled thin-walled columns for crashworthiness designs. *Finite Elements in Analysis and Design*, 46(9): 698–709.

Carruthers, J. J., Kettle, A. P., and Robinson, A. M. (1998). Energy absorption capability and crashworthiness of composite material structures: A review. *Applied Mechanics Reviews*, 51(10): 635–649.

Chen, W., and Wierzbicki, T. (2001). Relative merits of single-cell, multi-cell and foam-filled thin-walled structures in energy absorption. *Thin-Walled Structures*, 39(4): 287–306.

Chou, C. (1998). *Honeycomb materials models for simulating responses of foams*. MD-48, AEC, Ford Motor Company.

Chung, J., and Waas, A. M. (2000). The inplane elastic properties of circular cell and elliptical cell honeycombs. *Acta Mechanica*, 144(1–2): 29–42.

Chung, Jaeung, and Waas, A. M. (2002)a. Compressive response of circular cell polycarbonate honeycombs under inplane biaxial static and dynamic loading. Part I: experiments. *International Journal of Impact Engineering,* 27(7): 729–754.

Chung, Jaeung, and Waas, A. M. (2002)b. Compressive response of honeycombs Under in-plane uniaxial static and dynamic loading, part 2: Simulations. *AIAA Journal*, 40(5): 974–980.

Corex-Honeycomb. (2018). Aluminium Honeycomb core material. Retrieved from *https://corex-honeycomb.co.uk/products-and-services/aluminium-honeycomb/*

Costas, M., Morin, D., Langseth, M., Romera, L., and Díaz, J. (2016). Axial crushing of aluminum extrusions filled with PET foam and GFRP. An experimental investigation. *Thin-Walled Structures,* 99: 45–57.

Cowper, G., and Symonds, P. (1957). Strain hardening and strain-rate effects in the impact loading of cantilever beam. *Brown University Division of Applied Mathematics*, 1–46.

Crutzen, Y., Inzaghi, A., Mogilevsky, M., and Albertini, C. (1996). Computer modelling of the energy absorption process in box-type structures under oblique impact. *Automotive Automation Limited (UK)*, 1293–1298.

Daneshi, G. ., and Hosseinipour, S. . (2002). Grooves effect on crashworthiness characteristics of thin-walled tubes under axial compression. *Materials & Design*, 23(7): 611–617.

Deqiang, S., Weihong, Z., and Yanbin, W. (2010). Mean out-of-plane dynamic plateau stresses of hexagonal honeycomb cores under impact loadings. *Composite Structures*, 92(11): 2609–2621.

Djamaluddin, F., Abdullah, S., and Ariffin, A. (2015). Multi objective optimization of foam-filled circular tubes for quasi-static and dynamic responses. *Latin American Journal*, 12(6): 1126–1143.

Djamaluddin, F., Abdullah, S., Ariffin, A. K., and Nopiah, Z. M. (2015). Non-linear finite element analysis of bitubal circular tubes for progressive and bending collapses. *International Journal of Mechanical Sciences*, 99: 228–236.

Eskandarian, A., Marzougui, D., and Bedewi, N. E. (1997). Finite element model and validation of a surrogate crash test vehicle for impacts with roadside objects. *International Journal of Crashworthiness*, 2(3): 239–258.

Evans, L. (1989). Passive comapred to active approaches to reducing occupant fatalities. In *12th international conference on experimental safety vehicles* (pp. 1–18).

Evans, L. (2001). Causal influence of car mass and size on driver fatality risk. *American Journal of Public Health*, 91(7): 1076–1081.

Fang, J., Gao, Y., Sun, G., Qiu, N., and Li, Q. (2015). On design of multi-cell tubes under axial and oblique impact loads. *Thin-Walled Structures*, 95: 115–126.

Galib, D. A., and Limam, A. (2004). Experimental and numerical investigation of static and dynamic axial crushing of circular aluminum tubes. *Thin-Walled Structures*, 42(8): 1103–1137.

Gameiro, C. P., and Cirne, J. (2007). Dynamic axial crushing of short to long circular aluminium tubes with agglomerate cork filler. *International Journal of Mechanical Sciences*, 49(9): 1029–1037.

Guillow, S. R., Lu, G., and Grzebieta, R. H. (2001). Quasi-static axial compression of thin-walled circular aluminium tubes. *International Journal of Mechanical Sciences*, 43(9): 2103–2123.

Han, D. C., and Park, S. H. (1999). Collapse behavior of square thin-walled columns subjected to oblique loads. *Thin-Walled Structures*, 35(3): 167–184.

Hanssen, A. G., Langseth, M., and Hopperstad, O. S. (2000). Static and dynamic crushing of square aluminium extrusions with aluminium foam filler. *International Journal of Impact Engineering*, 24(4): 347–383.

Hayduk, R. J., and Wierzbicki, T. (1984). Extensional collapse modes of structural members. *Computers & Structures*, 18(3): 447–458.

He, Q., Feng, J., Zhou, H., and Tian, G. (2018). Numerical study on the dynamic behavior of circular honeycomb structure with concentrated filling inclusions defects. *Journal of Mechanical Science and Technology*, 32(8): 3727–3735.

HKS. (2006). Getting Started with ABAQUS. *Hibbitt, Karlsson & Sorensen, Inc*. Retrieved from *https://books.google.com.my/books/about/Getting_Started_with_ABAQUS_Standard.html?id=Qo4YAQAAMAAJ&redir_esc=y*

Hong, S.-T., Pan, J., Tyan, T., and Prasad, P. (2008). Dynamic crush behaviors of aluminum honeycomb specimens under compression dominant inclined loads. *International Journal of Plasticity*, 24(1): 89–117.

Hou, S., Li, Q., Long, S., Yang, X., and Li, W. (2008). Multiobjective optimization of multi-cell sections for the crashworthiness design. *International Journal of Impact Engineering*, 35(11): 1355–1367.

Hu, L. L., He, X. L., Wu, G. P., and Yu, T. X. (2015). Dynamic crushing of the circular-celled honeycombs under out-of-plane impact. *International Journal of Impact Engineering*, 75: 150–161.

Hu, L. L., Yu, T. X., Gao, Z. Y., and Huang, X. Q. (2008). The inhomogeneous deformation of polycarbonate circular honeycombs under in-plane compression. *International Journal of Mechanical Sciences*, 50(7): 1224–1236.

Hui, D. (1986). Design of beneficial geometric imperfections for elastic collapse of thin-walled box columns. *International Journal of Mechanical Sciences*, 28(3): 163–172.

Ismail, A. (2008). Energy absorption of foam-filled steel extrusion under quasi-static oblique loading. *International Journal of Engineering and Technology*, 5(1): 11–24.

Jacob, G. C., Fellers, J. F., Simunovic, S., and Starbuck, J. M. (2002). Energy absorption in polymer composites for automotive crashworthiness. *Journal of Composite Materials*, 36(7): 813–850.

Jacob, G. C. G. C., Starbuck, J. M. M., Simunovic, S., and Fellers, J. F. J. F. (2003). Energy absorption in glass-reinforced continuous strand mat composites. *Journal of Applied Polymer Science*, 90(12): 3222–3232.

Jensen, Ø., Langseth, M., and Hopperstad, O. S. (2004). Experimental investigations on the behaviour of short to long square aluminium tubes subjected to axial loading. *International Journal of Impact Engineering*, 30(8–9): 973–1003.

Johnson, W., and Reid, S. R. (1978). Metallic energy dissipating systems. *Applied Mechanics Reviews*, 31(3): 277–287.

Johnson, W., and Soden, P. (1977). Inextensional collapse of thin-walled tubes under axial compression. *The Journal of Strain*, 12(4): 317–330.

Jusuf, A., Dirgantara, T., Gunawan, L., and Putra, I. S. (2015). Crashworthiness analysis of multi-cell prismatic structures. *International Journal of Impact Engineering*, 78: 34–50.

Kecman, D. (1983). Bending collapse of rectangular and square section tubes. *International Journal of Mechanical Sciences*, 25(9–10): 623–636.

Khan, M. K., Baig, T., and Mirza, S. (2012). Experimental investigation of in-plane and out-of-plane crushing of aluminum honeycomb. *Materials Science and Engineering: A*, 539: 135–142.

Kim, H.-S. (2001). *Crash behavior of three dimensional thin-walled structures under combined loading*. Massachusetts Institute of Technology.

Kim, H.-S. (2002). New extruded multi-cell aluminum profile for maximum crash energy absorption and weight efficiency. *Thin-Walled Structures*, 40(4): 311–327.

Kim, H.-S., and Wierzbicki, T. (2000). Numerical and analytical study on deep biaxial bending collapse of thin-walled beams. *International Journal of Mechanical Sciences*, 42(10): 1947–1970.

Kim, H.-S., and Wierzbicki, T. (2001). Crush behavior of thin-walled prismatic columns under combined bending and compression. *Computers & Structures*, 79(15): 1417–1432.

Langseth, M., and Hopperstad, O. S. (1996). Static and dynamic axial crushing of square thin-walled aluminium extrusions. *International Journal of Impact Engineering*, 18(7–8): 949–968.

Langseth, M., Hopperstad, O. S., and Berstad, T. (1999). Crashworthiness of aluminium extrusions: validation of numerical simulation, effect of mass ratio and impact velocity. *International Journal of Impact Engineering*, 22(9–10): 829–854.

Li, Z., Rakheja, S., and Shangguan, W.-B. (2019). Study on crushing behaviors of foam-filled thin-walled square tubes with different types and number of initiators under multiple angle loads. *Thin-Walled Structures*, 145: 106376.

Liang, S., and Chen, H. L. (2006). Investigation on the square cell honeycomb structures under axial loading. *Composite Structures*, 72(4): 446–454.

Lin, T.-C., Chen, T.-J., and Huang, J.-S. (2012). In-plane elastic constants and strengths of circular cell honeycombs. *Composites Science and Technology*, 72(12): 1380–1386.

Liu, L., Wang, H., and Guan, Z. (2015). Experimental and numerical study on the mechanical response of Nomex honeycomb core under transverse loading. *Composite Structures*, 121: 304–314.

Liu, Ying, and Zhang, X.-C. (2009). The influence of cell micro-topology on the in-plane dynamic crushing of honeycombs. *International Journal of Impact Engineering*, 36(1): 98–109.

Liu, Yucheng. (2008). Crashworthiness design of multi-corner thin-walled columns. *Thin-Walled Structures*, 46(12): 1329–1337.

Lu, G., and Yu, T. (2003). Energy absorption of stuctures and materials, CRC Press.

Mahmoodi, A., Shojaeefard, M. H., and Saeidi Googarchin, H. (2016). Theoretical development and numerical investigation on energy absorption behavior of tapered multi-cell tubes. *Thin-Walled Structures*, 102: 98–110.

Malaysia New Vehicles Registered - Road Transport Department Malaysia. (2019). *Trading Economics*. Retrieved from *https://tradingeconomics.com/malaysia/car-registrations*

Mantena, P. R., and Mann, R. (2003). Impact and dynamic response of high-density structural foams used as filler inside circular steel tube. *Composite Structures*, 61(4): 291–302.

Mellquist, E. C., and Waas, A. M. (2004). Size effects in the crushing of honeycomb structures. In *Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference* (Vol. 2, pp. 1388–1401). Reston, Virigina: American Institute of Aeronautics and Astronautics.

Ministry of Transport Malaysia. (2017). Annual Transport Statistics. Retrieved from *http://www.mot.gov.my/en/resources/yearly-statistic*

Mirfendereski, L., Salimi, M., and Ziaei-Rad, S. (2008). Parametric study and numerical analysis of empty and foam-filled thin-walled tubes under static and dynamic loadings. *International Journal of Mechanical Sciences*, 50(6): 1042–1057.

Mohammadiha, O., Beheshti, H., and Aboutalebi, F. H. (2015). Multi-objective optimisation of functionally graded honeycomb filled crash boxes under oblique impact loading. *International Journal of Crashworthiness*, 20(1): 44–59.

Mozafari, H., Khatami, S., Molatefi, H., Crupi, V., Epasto, G., and Guglielmino, E. (2016). Finite element analysis of foam-filled honeycomb structures under impact loading and crashworthiness design. *International Journal of Crashworthiness*, 21(2): 148–160.

Nagel, G. M., and Thambiratnam, D. P. (2004). A numerical study on the impact response and energy absorption of tapered thin-walled tubes. *International Journal of Mechanical Sciences*, 46(2): 201–216.

Nagel, G. M., and Thambiratnam, D. P. (2006). Dynamic simulation and energy absorption of tapered thin-walled tubes under oblique impact loading. *International Journal of Impact Engineering*, 32(10): 1595–1620.

Najafi, A., and Rais-Rohani, M. (2011). Mechanics of axial plastic collapse in multi-cell, multi-corner crush tubes. *Thin-Walled Structures*, 49(1): 1–12.

National Highway Traffic Safety Administration - NHTSA. (2015). Traffic Safety Facts 2014: A Compilation of Motor Vehicle Crash Data from theFatality Analysis Reporting System and the General Estimates System. Retrieved from *https://crashstats.nhtsa.dot.gov/Api/Public/Publication/812261*

Nia, A. A., and Parsapour, M. (2013). An investigation on the energy absorption characteristics of multi-cell square tubes. *Thin-Walled Structures*, 68: 26–34.

Nia, A. A., and Sadeghi, M. Z. (2013). An experimental investigation on the effect of strain rate on the behaviour of bare and foam-filled aluminium honeycombs. *Materials & Design (1980-2015)*, 52: 748–756.

Ohkubo, Y., Akamatsu, T., and Shirasawa, K. (1974). Mean crushing strength of closed-hat section members. In *SAE Technical Papers* (p. 740040). Detroit: SAE Technical Paper.

Olabi, A. G., Morris, E., Hashmi, M. S. J., and Gilchrist, M. D. (2008). Optimised design of nested circular tube energy absorbers under lateral impact loading. *International Journal of Mechanical Sciences*, 50(1): 104–116.

Oruganti, R. K., and Ghosh, A. K. (2008). FEM analysis of transverse creep in honeycomb structures. *Acta Materialia*, 56(4): 726–735.

Paik, J. K., Thayamballi, A. K., and Kim, G. S. (1999). The strength characteristics of aluminum honeycomb sandwich panels. *Thin-Walled Structures*, 35(3): 205–231.

Pirmohammad, S., and Marzdashti, S. E. (2016). Crushing behavior of new designed multi-cell members subjected to axial and oblique quasi-static loads. *Thin-Walled Structures*, 108: 291–304.

Pletschen, B., Herrmann, R., Kallina, I., and Zeidler, F. (1990). The significance of frontal offset collisions in real world accidents. In *SAE Technical Papers* (p. 900411).

Qin, Q. H., and Wang, T. J. (2009). A theoretical analysis of the dynamic response of metallic sandwich beam under impulsive loading. *European Journal of Mechanics, A/Solids*, 28(5): 1014–1025.

Qin, Q. H., Wang, T. J., and Zhao, S. Z. (2009). Large deflections of metallic sandwich and monolithic beams under locally impulsive loading. *International Journal of Mechanical Sciences,* 51(11–12): 752–773.

Qiu, N., Gao, Y., Fang, J., Feng, Z., Sun, G., and Li, Q. (2015). Crashworthiness analysis and design of multi-cell hexagonal columns under multiple loading cases. *Finite Elements in Analysis and Design*, 104: 89–101.

Reid, S. R., and Reddy, T. Y. (1986). Static and dynamic crushing of tapered sheet metal tubes of rectangular cross-section. *International Journal of Mechanical Sciences*, 28(9): 623–637.

Reyes, A., Hopperstad, O. S., and Langseth, M. (2004). Aluminum foam-filled extrusions subjected to oblique loading: experimental and numerical study. *International Journal of Solids and Structures*, 41(5–6): 1645–1675.

Reyes, A., Langseth, M., and Hopperstad, O. S. (2002). Crashworthiness of aluminum extrusions subjected to oblique loading: experiments and numerical analyses. *International Journal of Mechanical Sciences*, 44(9): 1965–1984.

Reyes, A., Langseth, M., and Hopperstad, O. S. (2003). Square aluminum tubes subjected to oblique loading. *International Journal of Impact Engineering*, 28(10): 1077–1106.

Robinson, S. (1997). Simulation model verification and validation: Increasing the users' confidence. In *Winter Simulation Conference Proceedings* (pp. 53–59). IEEE Computer Society.

Salehghaffari, S., Tajdari, M., Panahi, M., and Mokhtarnezhad, F. (2010). Attempts to improve energy absorption characteristics of circular metal tubes subjected to axial loading. *Thin-Walled Structures*, 48(6): 379–390.

Santosa, S. P., Wierzbicki, T., Hanssen, A. G., and Langseth, M. (2000). Experimental and numerical studies of foam-filled sections. *International Journal of Impact Engineering*, 24(5): 509–534.

Seitzberger, M., Rammerstorfer, F. G., Gradinger, R., Degischer, H. P., Blaimschein, M., and Walch, C. (2000). Experimental studies on the quasi-static axial crushing of steel columns filled with aluminium foam. *International Journal of Solids and Structures*, 37(30): 4125–4147.

Shariatpanahi, M., Masoumi, A., and Ataei, A. (2008). Optimum design of partially tapered rectangular thin-walled tubes in axial crushing. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 222(2): 285–291.

Sheriff, N. M., Gupta, N. K., Velmurugan, R., and Shanmugapriyan, N. (2008). Optimization of thin conical frusta for impact energy absorption. *Thin-Walled Structures*, 46(6): 653–666.

Shiravand, A., and Asgari, M. (2019). Hybrid metal-composite conical tubes for energy absorption; theoretical development and numerical simulation. *Thin-Walled Structures,* 145: 106442.

Singace, A. ., El-Sobky, H., and Petsios, M. (2001). Influence of end constraints on the collapse of axially impacted frusta. *Thin-Walled Structures*, 39(5): 415–428.

Song, J., and Guo, F. (2013). A comparative study on the windowed and multi-cell square tubes under axial and oblique loading. *Thin-Walled Structures*, 66: 9–14.

Stucki, S. L., Hollowell, W. T., and Fessahaie, O. (1998). Determination of frontal offset test conditions based on crash data. *National Highway Traffic Safety Administration*, (208).

Summers, S. M., Prasad, A., and Hollowell, W. T. (2001). NHTSA's Research Program for Vehicle Aggressivity and Fleet Compatibility. *NHTSA Research and Development Web site*. Retrieved from *https://www.nrd.nhtsa.dot.gov/pdf/esv/esv17/Proceed/00179.pdf*

Sun, G., Jiang, H., Fang, J., Li, G., and Li, Q. (2016). Crashworthiness of vertex based hierarchical honeycombs in out-of-plane impact. *Materials & Design*, 110: 705–719.

Tabacu, S. (2016). Analysis of circular tubes with rectangular multi-cell insert under oblique impact loads. *Thin-Walled Structures,* 106: 129–147.

Tang, Z., Liu, S., and Zhang, Z. (2013). Analysis of energy absorption characteristics of cylindrical multi-cell columns. *Thin-Walled Structures*, 62: 75–84.

Tani, M., and Funahashi, A. (1978). Energy absorption by the plastic deformation of body structural members. In *SAE Technical Papers*.

Tarlochan, F. (2007). *Design, fabrication and evaluation of composite sandwich panels for crashworthiness,*. Universiti Putra Malaysia, Malaysia.

Tho, C. H. (2006). Crashworthiness design optimization using surrogate models, (August).

Tisza, M., and Czinege, I. (2018). Comparative study of the application of steels and aluminium in lightweight production of automotive parts. *International Journal of Lightweight Materials and Manufacture*, 1(4): 229–238.

Tolouei, R., Maher, M., and Titheridge, H. (2013). Vehicle mass and injury risk in two-car crashes: A novel methodology. *Accident Analysis and Prevention*, 50: 155–166.

Tran, T. (2017). Crushing analysis under multiple impact loading cases for multi-cell triangular tubes. *Thin-Walled Structures*, 113: 262–272.

Triantos, D., and Michaels, M. (1999). Design and fabrication of an aluminum engine cradle for a general motors vehicle. In *SAE Technical Papers* (p. 9). SAE Technical Paper Series.

Usta, F., and Turkmen, H. S. (2017). Crash behavior of nested tube structures with various cross sections. In *2017 8th International Conference on Recent Advances in Space Technologies (RAST)* (pp. 23–27). IEEE.

Wallentowitz, H., and Adam, H. (1996). Predicting the crashworthiness of vehicle structures made by lightweight design materials and innovative joining methods. *International Journal of Crashworthiness*, 163–180.

Wierzbicki, T., and Abramowicz, W. (1983). On the crushing mechanics of thi-n-walled structures. *Journal of Applied Mechanics, Transactions ASME*, 50(4): 727–734.

Wierzbicki, Tomasz. (1983). Crushing analysis of metal honeycombs. *International Journal of Impact Engineering*, 1(2): 157–174.

Wierzbicki, Tomasz, and Abramowicz, W. (1989). *The Mechanics of Deep Plastic Collapse of Thin-walled S tructures*. *Structural Failure*. New York: Wiley.

Wierzbicki, Tomasz, and Bhat, S. (1986). A moving hinge solution for axisymmetric crushing of tubes. *International Journal of Mechanical Sciences*, 28(3): 135–151.

Wierzbicki, Tomasz, Bhat, S., and Abramowicz, W. (1992). Alexander revisited—a two folding elements model of progressive crushing of tubes. *International Journal of Solids and Structures*, 29(24): 3269–3288.

Wierzbicki, Tomasz, Recke, L., Abramowicz, W., Gholami, T., and Huang, J. (1994). Stress profiles in thin-walled prismatic columns subjected to crush loading-II. Bending. *Computers & Structures*, 51(6): 625–641.

Witteman, W. J. (1999). *Improved Vehicle Crashworthiness Design by Control of the Energy Absorption for Different Collision Situations*.

World Health Organization. (2015). *Global status report on road safety 2015*. *World Health Organization*. World Health Organization.

Wu, E. (1995). Plastic buckling of metallic honeycombs. *Journal of Chinese Society of Mechanical Engineers*, 16(1): 11–20.

Wu, E., and Jiang, W.-S. (1997). Axial crush of metallic honeycombs. *International Journal of Impact Engineering*, 19(5–6): 439–456.

Xiang, J., and Du, J. (2017). Energy absorption characteristics of bio-inspired honeycomb structure under axial impact loading. *Materials Science and Engineering: A*, 696: 283–289.

Xu, S., Beynon, J. H., Ruan, D., and Yu, T. X. (2012). Strength enhancement of aluminium honeycombs caused by entrapped air under dynamic out-of-plane compression. *International Journal of Impact Engineering*, 47: 1–13.

Xu, Shanqing, Beynon, J. H., Ruan, D., and Lu, G. (2012). Experimental study of the out-of-plane dynamic compression of hexagonal honeycombs. *Composite Structures*, 94(8): 2326–2336.

Yasui, Y. (2000). Dynamic axial crushing of multi-layer honeycomb panels and impact tensile behavior of the component members. *International Journal of Impact Engineering*, 24(6–7): 659–671.

Yin, H., Wen, G., Hou, S., and Chen, K. (2011). Crushing analysis and multiobjective crashworthiness optimization of honeycomb-filled single and bitubular polygonal tubes. *Materials & Design*, 32(8–9): 4449–4460.

Zarei, H., and Kröger, M. (2008). Optimum honeycomb filled crash absorber design. *Materials & Design*, 29(1): 193–204.

Zarei, H. R., and Kröger, M. (2006). Multiobjective crashworthiness optimization of circular aluminum tubes. *Thin-Walled Structures*, 44(3): 301–308.

Zarei, H. R., and Kröger, M. (2008). Bending behavior of empty and foam-filled beams: Structural optimization. *International Journal of Impact Engineering*, 35(6): 521–529.

Zhang, J., and Ashby, M. F. (1992). The out-of-plane properties of honeycombs. *International Journal of Mechanical Sciences*, 34(6): 475–489.

Zhang, X., and Cheng, G. (2007). A comparative study of energy absorption characteristics of foam-filled and multi-cell square columns. *International Journal of Impact Engineering*, 34(11): 1739–1752.

Zhang, X., Cheng, G., You, Z., and Zhang, H. (2007). Energy absorption of axially compressed thin-walled square tubes with patterns. *Thin-Walled Structures*, 45(9): 737–746.

Zhang, X., Cheng, G., and Zhang, H. (2006). Theoretical prediction and numerical simulation of multi-cell square thin-walled structures. *Thin-Walled Structures*, 44(11): 1185–1191.

Zhang, X., and Zhang, H. (2013). Energy absorption of multi-cell stub columns under axial compression. *Thin-Walled Structures*, 68: 156–163.

Zhang, Y., Lu, M., Wang, C. H., Sun, G., and Li, G. (2016). Out-of-plane crashworthiness of bio-inspired self-similar regular hierarchical honeycombs. *Composite Structures*, 144: 1–13.

Zhang, Z., Liu, S., and Tang, Z. (2009). Design optimization of cross-sectional configuration of rib-reinforced thin-walled beam. *Thin-Walled Structures*, 47(8–9): 868–878.

Zhou, J., Qin, R., and Chen, B. (2019). Energy absorption properties of multi-cell thin-walled tubes with a double surface gradient. *Thin-Walled Structures*, 145: 106386.

Zhou, W., Craig, J., and Hanagud, S. (1991). Crashworthy behavior of graphite/epoxy composite sine wave webs. In *32nd Structures, Structural Dynamics, and Materials Conference*. Reston, Virigina: American Institute of Aeronautics and Astronautics.